



LAWRENCE  
LIVERMORE  
NATIONAL  
LABORATORY

# 4 1/2 D Fokker-Planck Transport Project

R. Harvey, Y. Petrov, R. Cohen, M. Dorf

April 14, 2015

DOE Workshop on Integrated Simulations for Magnetic Fusion  
Energy Sciences  
Rockville, MD, United States  
June 2, 2015 through June 4, 2015

## **Disclaimer**

---

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

## 4½ D Fokker-Planck Transport Project

R.W. Harvey, Yu.V. Petrov, R.H. Cohen(CompX), M. Dorf(LLNL), with Collaborators

*DOE Workshop in Integrated Simulations for MFE Sciences. Oral Presentation Requested*

**Objective:** Many key experimental plasma diagnostics are sensitive to kinetic velocity distributions of the plasma particles, providing key validations of the physics understanding. The 4½D Fokker-Planck Transport (4DFPT) project goal is to calculate accurate gyro-averaged kinetic electron and ion distribution functions for toroidally symmetric fusion energy plasmas across the whole plasma, compatible with both supercomputing and laboratories computational resources. Non-toroidal symmetric edge phenomena will all be addressed, hence the 4½D. An objective is to provide a robust, sufficiently accurate, computationally tractable, kinetic distribution model to be useful for routine interpretation of experimental data. Time-dependent and steady-state ion and electron continuum distributions at the transport time scale will be obtained, including crucial NBI/RF/fusion/Ohmic auxiliary heating sources.

**Methods:** Such a project has been partially realized with the widely used multi-species CQL3D finite-orbit-width (FOW) bounce-average Fokker-Planck code[1]. However, strictly 3D (v,theta,rho), with bounce-averaging are significant restrictions regards whole device modeling. Application for whole device modeling can be achieved by coupling CQL3D with the non-bounce-averaged 4/5D COGENT [2-4] neoclassical code, each code operating in their domains of valid approximation, and including the important effects of neutral gas. Neutral particle effects will be treated by coupling with UEDGE[7] and/or GTNEUT[8,9] informed by nonthermal plasma distributions. CQL3D is primarily oriented towards RF, NB/fusion and Etor sources which are major factors in production of the nonthermal distributions. It is coupled to the general RF ray tracing code GENRAY[] and full wave RF codes AORSA[ ] and TORIC[ ]. NB and fusion particle sources are calculated internally. CQL3D/COGENT also provide the important neoclassical transport and particle loss influences on kinetic distributions. Diffusion coefficients for classical and anomalous transport are also readily incorporated. Toroidally symmetric equilibria consistent with RF/NB/fusion/applied-Etor driven plasma currents will form a basis for the particle orbits. Code and physics validation is achieved by comparison of the derived synthetic diagnostic signals against energy and pitch angle dependent experimental plasma diagnostics.

Moreover, important non-toroidally-symmetric effects near the plasma periphery, such as ripple, metal limiters, and RF antennas, can be included through the 5D COGENT code. Nonthermal plasma sheath formation at divertor surfaces have previously been simulated with the FPET Fokker-Planck collisions code in 3d (v,theta,distance-along-B) [Kupfer] capturing some of the effects to be further addressed with the COGENT part of the proposed code suite.

All present-day FP codes use various approximations because a direct solve of the relevant 6D kinetic equation (3 spatial + 3 velocity) is formidable even for modern super-computers. Speedup of the proposed calculations is achieved by averaging (1) in the toroidal direction, (2) over gyro-angle, and (3) with CQL3D for low collisionality particles, over particle bounce; this gives distributions valid on the slower collision and transport time-scales. We are proposing to exploit the best features of two finite-volume-discretization FP codes --- CQL3D-FOW and COGENT, both based on guiding-center orbits --- which will provide a unified kinetic description across all regions of plasma, and also cover a broad energy range relevant to nonthermal tail particle distributions from NBI and RF plasma heating.

**Specifics:** The bounce-average FP code CQL3D developed by CompX is used by many national laboratories, universities and private companies inside and outside the U.S. The code is favored by experimentalists because of (1) physics-based modeling of RF/NBI induced nonthermal distribution functions, (2) its large set of synthetic diagnostics tools, (3) speed, (4) simplicity of use starting from a set of run templates, and (5) ready support from CompX. It is also coupled to other software such as the Plasma State, and is part of the SciDAC Integrated Plasma Simulator project. Rapid execution is

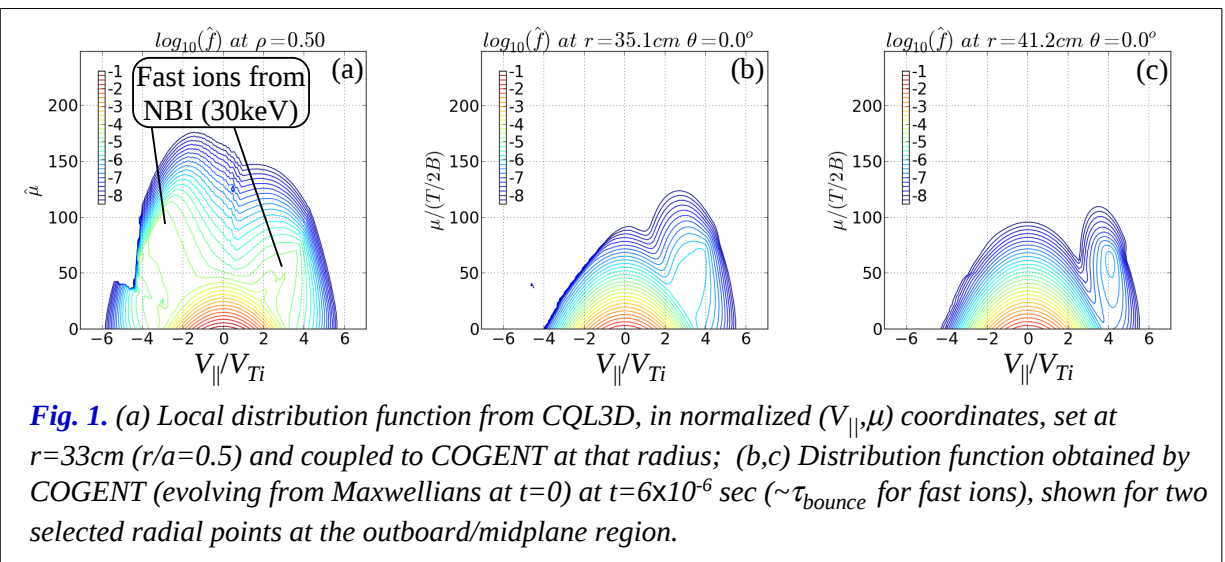
achieved by averaging the kinetic equations over all periodic coordinates, under the assumption of low collisionality, which is typically valid for 90% of the plasma radius. On the other hand, such bounce-average formalism is not suitable in conditions of higher collisionality or open flux surfaces, that is, at low velocities or at the plasma edge, for which COGENT has been developed.

COGENT is a 4/5D neoclassical edge code being developed at LLNL and LBL for plasma edge modeling. The present version of the code models a nonlinear axisymmetric 4D gyrokinetic equation coupled to the long-wavelength limit of the gyro-Poisson equation. There are two configuration dimensions: flux surface coordinate and poloidal angle, and two velocity-space dimensions: parallel velocity and magnetic-moment. In the 5D instantiation, toroidal averaging is omitted. The divertor version of the code is presently being tested in cross-separatrix neoclassical simulations including effects of the X-point geometry and fully nonlinear FP collisions.

The coupling between the two codes will be based on iterations. CQL3D code will normally obtain solutions over most of the plasma,  $r/a < 0.9$  (giving short computer runs), while COGENT will calculate distribution functions in the higher collisionality edge plasma (more CPU-intensive runs). Additional coupling will utilize a boundary in velocity space: COGENT will thus be used in the limited velocity range where bounce-averaging is invalid (up to a few  $V_{\text{thermal}}$  and near the plasma edge), while the faster CQL3D can accurately handle the range up to  $20 \cdot V_{\text{thermal}}$  and beyond, within its range of validity. The auxiliary heating sources, experimental modeling features, and synthetic diagnostics from CQL3D will be interfaced to COGENT. This approach will provide access to a set of powerful synthetic diagnostic tools which have become very popular among experimentalists, users of CQL3D, but will now include the whole plasma out to the plasma vacuum chamber. Neoclassical physics, e.g., bootstrap current toroidal and radial electric field/toroidal rotation, RF/NBI components, important finite-orbit-width power deposition broadening and wall losses, will be addressed. Important RF full-wave diffusion and pinch terms will be addressed through collaboration with RF-SciDAC. Total level of support required for the 4DFPT demonstration project is 1.2 FTE for 3 years..

**Initial Results:** Initial coupling results in radius between CQL3D and COGENT, shown in Fig. 1, have been obtained under a FY13 Phase I SBIR project, and this proposal will build on the results there obtained, and on the working relationship formed between the project members.

**Applications:** Code validation efforts will be conducted against experimental results in the major US tokamaks. An objective is to engage the fusion community in code use for the interpretation of toroidal plasma devices, in particular, experimentalists and graduate students. From past experience with CQL3D/GENRAY, such codes are an effective way of introducing graduate students to laboratory and enterprise scale computing.



A principle application will also be calculation of ITER heating and current drive profiles and fast particles losses, for plasma driven by fusion, NB, ICRF, LH, and EC systems, and with plasma radial transport losses calculated from physics-based levels of microturbulence.

Prepared by LLNL under Contract DE-AC52-07NA27344.

## References:

- [1] R.W. Harvey and M.G. McCoy, The CQL3D Fokker-Planck Code, Proc. of IAEA Technical Committee Meeting on Advances in Simulation and Modeling of Thermonuclear Plasmas, Montreal, 1992, p. 489-526, IAEA, Vienna (1993); [www.compxco.com/cql3d.html](http://www.compxco.com/cql3d.html); Google CQL3D CompX.
- [2] Dorr M.R., Cohen R.H., Colella P., Dorf M.A., Hittinger J. and Martin D.F., "Numerical simulation of phase space advection in gyrokinetic models of fusion plasmas", Proc. SciDAC 2010 Conf., Tennessee, (2010). Available at [http://computing.ornl.gov/workshops/scidac2010/papers/math m dorr.pdf](http://computing.ornl.gov/workshops/scidac2010/papers/math%20m%20dorr.pdf)
- [3] Dorf M., Cohen R.H., Dorr M., Rognlien T., Hittinger J., Compton J., Colella P., Martin D. and McCorquodale P. "Simulation of neoclassical transport with the continuum gyrokinetic code COGENT", Phys. Plasmas **20**, 012513 (2013).
- [4] M.A. Dorf , R.H. Cohen, M. Dorr, T. Rognlien, J. Hittinger, J. Compton, P. Colella, D. Martin and P. McCorquodale, "Numerical modelling of geodesic acoustic mode relaxation in a tokamak edge", Nucl. Fusion **53**, 063015 (2013).
- [5] G.M. Staebler, J.E. Kinsey, and R.E. Waltz, "A Theory Based Transport Model With Comprehensive Physics," *Phys. Plasmas* **14**, 055909 (2007).
- [6] R. E. Waltz, E. M. Bass, and G. M. Staebler, "Quasilinear model for energetic particle diffusion in radial and velocity space," *Phys. Plasmas* **20**, 042510 (2013).
- [7] T. D. Rognlien, D. D. Ryutov, N. Mattor, and G. D. Porter, *Phys. Plasmas* **6**, 1851 (1999).
- [8] John Mandrekas, "GTNEUT: A Code for the Calculation of Neutral Particle Transport in Plasmas Based on the Transmission & Escape Probability Method", *Computer Physics Comm.* **161**, 36-64 (2004); Dingkan Zhang, J. Mandrekas, and W.M. Stacey, "Higher order approximations of the transmission and escape probability method for neutral particle transport in edge plasmas", *Phys. of Plasmas* **13**, 062509 (2006).
- [9] Z.W. Friis, W.M. Stacey, A.W. Leonard, and M.E. Rensink, "Analysis of neutral particle recycling and pedestal fueling in a H-mode DIII-D discharge", *Phys. of Plasmas* **17**, 022507 (2010).